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Agricultural practices for growing kenaf (Hibiscus cannabinus L.) in Iowa: II. fiber composition and quality

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Abstract

The demand for natural fibers is increasing worldwide as markets respond to the need to replace non-renewable sources. Kenaf (Hibiscus cannabinus L.) is a promising biorenewable resource for producing natural fibers. Few studies have investigated the crop when grown at latitudes above 40° and in the Midwest. The objectives of this study were to assess the influence of management practices on fiber (bast and core lignocellulose) composition, carbon (C), nitrogen (N), and total ash concentration. Cultivars 'Tainung 2' and 'Whitten' were planted in Boone County, IA in 2014 and 2015 at 247,000 or 371,000 seed ha-1, in 38-cm or 76-cm rows, and fertilized with N at 0, 56, 112, 168, or 224 kg ha-1. Treatments were in a factorial design with four replications in two years. Stem bast and core lignocellulose concentrations, total ash, and C:N ratio were determined at harvest. Variety or interactions of variety with management practices influenced most parameters. Increased N fertilization decreased bast cellulose concentration, but increased core cellulose concentration. Hemicellulose concentration in core was greater than in bast. Ash concentration decreased as N fertilization rate increased, and interacted with seeding rate and variety. The implications of these observations are directly related to markets and desired kenaf end-use products. Variety and management interactions influence kenaf fiber quality, and consequently are important considerations for kenaf producers and processors.

Keywords

ash, kenaf, N rates, lignocellulose, row spacing, seeding rate, variety

Disciplines

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Comments

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Agricultural Practices for Growing Kenaf (*Hibiscus cannabinus* L.) in Iowa: II. Fiber Composition and Quality

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ABSTRACT

The demand for natural fibers is increasing worldwide as markets respond to the need to replace non-renewable sources. Kenaf (*Hibiscus cannabinus* L.) is a promising biorenewable resource for producing natural fibers. Few studies have investigated the crop when grown at latitudes above 40° and in the Midwest. The objectives of this study were to assess the influence of management practices on fiber (bast and core lignocellulose) composition, carbon (C), nitrogen (N), and total ash concentration. Cultivars 'Tainung 2' and 'Whitten' were planted in Boone County, IA in 2014 and 2015 at 247,000 or 371,000 seed ha^{-1}, in 38-cm or 76-cm rows, and fertilized with N at 0, 56, 112, 168, or 224 kg ha^{-1}. Treatments were in a factorial design with four replications in two years. Stem bast and

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core lignocellulose concentrations, total ash, and C:N ratio were determined at harvest. Variety or interactions of variety with management practices influenced most parameters. Increased N fertilization decreased bast cellulose concentration, but increased core cellulose concentration. Hemicellulose concentration in core was greater than in bast. Ash concentration decreased as N fertilization rate increased, and interacted with seeding rate and variety. The implications of these observations are directly related to markets and desired kenaf end-use products. Variety and management interactions influence kenaf fiber quality, and consequently are important considerations for kenaf producers and processors.

Keywords: ash, kenaf, N rates, lignocellulose, row spacing, seeding rate, variety

Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; C, carbon; DM, dry matter; N, nitrogen; NDF, neutral detergent fiber.

Core Ideas

- Two kenaf cultivars were compared for stem fiber composition under combinations of planting rate, row spacings, and N fertilization rate
- Variety and variety interactions with management practices influenced lignocellulose and ash concentrations of kenaf bast and core fiber
- Nitrogen rate and N rate interactions with management practices influenced lignocellulose and ash concentrations of kenaf bast and core fiber
- Variety selection and management practices are important for kenaf producers and processors

Kenaf is an annual, dicot, herbaceous crop, originally from Africa (Cheng et al., 2004) but 73% of world production now occurs in India and China (INFO, 2016). Kenaf contains two types of fiber, bast and core. Bast fibers are located in the outer layer of the kenaf stem and are the portion of the plant most widely used for the industrial production of paper, pulp, textile, and rope (Bel-Berger et al., 1999). The core, the inner part of the stem, has often been considered a byproduct by industry; however, the core has the potential to be used other ways, such as absorbent material applications because of its short and porous fibers (Monti and Alexopoulou, 2013). Bast and core can be used separately or together in the production of bioplastics, biocomposites, or biofuels (Saba et al., 2015). Kenaf has been produced in the U.S. Kenaf was introduced in the U.S. during the Second World War to produce cordage (Dempsey, 1975), but has received little attention since. It is still grown in the U.S., mostly in the Southern states, such as Georgia, Texas, Mississippi, and New Mexico (Webber et al., 2002). It was estimated that growing kenaf in the U.S. cost $293 per acre and provided revenue of $396 per acre with a $103 per acre profit (Bazen et al., 2006). Despite this apparent profitability, kenaf is not commonly produced in the U.S. Perhaps a primary reason is that production strategies and agronomic management recommendations are lacking.

Some research has been done to develop improved management practices for kenaf yield, but these studies were located in only a few U.S. regions. Studies have focused on management practices, such as planting time, row spacing, population density, fertilization, irrigation, or crop rotation practices in Florida (Joyner and Wilson, 1967), Nebraska (Williams, 1966), California (Bhangoo et al., 1986), Mississippi (Baldwin and Graham, 2006), Maryland (Campbell and White, 1982; Massey, 1974), New-Mexico (Lauriault and Puppala, 2009), and North Carolina (Jordan et al., 2005). Numerous studies on kenaf management have been done outside the U.S., i.e., Spain (Manzanares et al., 1997; Moreno et al., 2004; Wood et al., 1983), Italy (Mambelli and Grandi, 1995), Greece (Alexopoulou et al., 2000; Danalatos and Archontoulis, 2010), and Australia (Carberry et al., 1992; Muchow and Carberry, 1993).

Little research has focused on agronomic management for kenaf production in the Great Plains and Midwest. Berti et al. (2013) showed that kenaf can produce stem yields of 10 Mg ha^{-1} when grown in North Dakota and estimated that it could be used to produce 1,400 L ha^{-1} of biofuel. Also, planting kenaf at 10,000 to 32,000 seed ha^{-1} in 30-cm rows was the best recommendation for growing kenaf in North Dakota (Berti et al., 2013). The studies in North Dakota used the variety 'Dowling', which was not a high-performing cultivar in Iowa (Bourguignon, 2016a), who reported that the varieties 'Tainung 2' and 'Whitten' were the most promising varieties when grown in Iowa. Therefore, the recommendations provided by Berti et al. (2013) may result in different outcomes when other cultivars are used (White et al., 1971; Alexopoulou et al., 2000).

Bourguignon et al. (2017) conducted a study in Iowa from 2004 to 2007, which investigated the influence of three row spacings, three seeding rates, three planting dates, and absence or presence of N fertilization. Nevertheless, several important knowledge gaps exist for producers interested in growing kenaf in the Midwest. In Bourguignon et al. (2017), the N treatments only included absence or presence of N fertilization (0 or 168 kg N ha^{-1}). Other investigations in the U.S. have reported kenaf response to N fertilization, with some studies showing N fertilization improved stem, cellulose, and lignin yield (Adamson et al., 1979), while others reported little or no influence on yield from N fertilizer application (Massey, 1974; Webber, 1996; Danalatos and Archontoulis, 2010). Investigations specifically conducted in Iowa and the Midwest have not addressed optimal N fertilization.

Bourguignon et al. (2017) used a single variety, Tainung 2. This cultivar was shown to be promising in Iowa (Bourguignon et al., 2016a) and it is one of the most commercialized cultivars in the world; however, 'Whitten', a variety developed by Mississippi State University (Baldwin et al., 2006) also showed good potential in Iowa. In contrast to Tainung 2 that has deeply divided leaves, Whitten retains the juvenile leaf shape, common to most of the kenaf varieties. This shape is undivided and does not resemble marijuana (*Cannabis sativa* L.), avoiding confusion and potential trouble with law enforcement officials, an important consideration for producers. Whitten could have other advantages, including being more economically competitive than Tainung 2 due to greater stem production potential. Baldwin et al. (2006) suggested that Whitten tends to have greater height and more resistance to powdery mildew than other cultivars. Additionally, Bourguignon et al. (2017) only reported stem height and diameter at the final harvest and, therefore, did not give any indication about plant growth over the growing season. It was shown that plant height, harvested at a certain date after planting, was consistent and significantly higher than previous dates (Ogbonnaya et al., 1998; Webber and Bledsoe, 2002b), and was sensitive to management practices, when grown in Greece (Danalatos and Archontoulis, 2010). This information has not previously been studied in Iowa. Although Bourguignon et al. (2017) reported the lignocellulose concentration in kenaf, the quantity of ash found in the dry bast and core material was not investigated. Ash concentration has been shown to be important for feedstock conversion into biofuel, because the ash presence can lead to fouling, corrosion, and erosion problems in the conversion processes (Mohan et al., 2006). Ash concentration in pulp is important for production of paper and must be within a limited range depending on the type of paper being produced. Additionally, Bourguignon et al. (2017) did not evaluate C and N concentrations in kenaf samples. Carbon and N concentrations help understanding of growth and development within the plant.

Given that previous kenaf studies conducted in Iowa had not examined several potentially important factors and their interactions, we conducted a field study on the influences of genotype, N fertilization rate, row spacing, and seeding rate on kenaf bast and core composition and development. In light of previous research, we hypothesized that variety, row spacing, seeding rate, and N fertilization rate will influence bast and core fiber quality. The objectives of this study were to determine the effect of agricultural practices (variety, row spacing, seeding rate and N fertilizer rate) on bast and core fiber composition (cellulose, hemicellulose, neutral and acid detergent fiber, acid detergent lignin, C, N, and ash) in the end-of-season biomass.

MATERIAL AND METHODS

Site, experiment, and local climate

The study was conducted at the Iowa State University Agronomy and Agricultural Engineering Research Farm, near Boone, Iowa (42°01’N, 93°46’W), on a Nicollet clay loam soil (fine-loamy, mixed, mesic Aquic Hapludoll). Detailed information on the experimental design, agronomic treatments, and field operations were provided by Bourguignon et al. (2019). The local air temperature and monthly cumulative precipitation were collected by a weather station [station A130209] located at the Agricultural Research Farm (ISU Ag Climate, 2014), approximately 3 km from the research site.

The experimental design was a split-block with four blocks, conducted in 2014 and 2015 on different sites. Kenaf variety ('Tainung 2', 'Whitten'), seeding rate (247,000 and 371,000 seed ha^{-1}), row spacing (38-cm and 76-cm rows) were the whole plot treatments and were in factorial combination, and 5 N fertilization rates (0, 56, 112, 168, 224 kg ha^{-1} N) were applied in perpendicular strips to the other treatments, across each block. The different N fertilized strips in combination with two varieties, two seeding rates, and two row spacings corresponded to the subplots (n = 160). The cultivars Tainung 2, originally from Taiwan, and Whitten, developed at Mississippi State University (Baldwin, 2006) were seeded at a depth of 2.5 cm in 2.7 m × 6 m plots on 10 June 2014 and 2 June 2015, when the top 10-cm soil temperature reached 15.6°C, and were evaluated for kenaf yield and morphology characteristics. A light tillage and formulated pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2, 6-dinitrobenzenamine) was applied at 2.3 L ha^{-1} to prevent weed growth were applied prior planting.

Data collection

Kenaf was harvested only once each year, after the first frost occurred. Two 3-meter rows were harvested by hand in each plot on 12 November 2014 and 24 November 2015, respectively, as described in depth by Bourguignon et al. (2019). Stalk number and wet weight were determined in the field on these two rows during each harvest.

A sample of three plants was collected and combined into one sample to represent each of the 160 plots. The three stalks were stripped and divided into bast and core for subsequent work. Samples were weighed, dried at 60°C until the moisture content was constant, and ground to 1-mm using a Thomas Wiley-Mill (Thomas Scientific, Swedesboro, NJ).

Bast and core samples were subjected to sequential fiber analysis using a modified ANKOM procedure (Vogel et al., 1999; Wilson et al., 2016), in order to estimate the concentration of lignocellulose in the cell walls of kenaf. A single 0.50 g dry sample was sealed in a filter bag (F57, ANKOM Technology, Macedon, NY) and used for sequential fiber analysis, concentrations of neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and insoluble ash. The bag was first soaked in a neutral detergent solution containing sodium sulfite and alpha-amylase, a digestive enzyme. Multiple rinses in tap water, deionized water and acetone were applied to the bag, before being dried and weighed. This first step allowed determination of NDF concentration.

The same bag was then refluxed in an acid detergent solution. A similar rinsing and drying protocol was applied to the bag and the residue remaining was used to calculate the ADF concentration. The difference between NDF and ADF concentration was used to calculate the hemicellulose concentration. Then, the sample was hydrolyzed with 72% sulfuric acid for three h, rinsed to remove cellulose, and weighed to determine the ADL concentration. Finally, the remaining part of the bag, containing insoluble ash, was combusted at 525 °C in a muffle furnace until carbon free and weighed. These steps were used to give an estimation of hemicellulose, cellulose, and lignin concentration.

Total ash was also determined on samples by weighing 1 g of ground dry biomass and using the same protocol as for insoluble ash. Using acetanilide as standard, a mixture of 3 to 5 mg sub-sample and tungsten trioxide was placed in Elemental Analyzer (Vario MICRO cube, Elementar Americas, Inc., Ronkonkoma, NY) to determine concentrations of N and C. All chemical measurements and yields were made on a dry matter (DM) basis and for this purpose, the dry matter of each bast and core sample (n = 320) was determined by weighing 1 g of ground material before and after being dried at 105 °C overnight.

Statistical analysis

The experimental was designed as a split-block with four replications and was analyzed by an analysis of variance to evaluate the agricultural practices effects on stem dry matter (DM), yield and fiber quality and quantity variables. PROC GLM in SAS System (SAS Institute Inc., Cary, NC) was used to perform all statistical analyses. Year and blocks were random variables, with block nested in year; all other parameters were fixed variables. Cellulose, hemicellulose, lignin, and ash concentrations and C:N ratio were analyzed separately for bast and core. Pearson correlation coefficients between selected, measured variables also were conducted. An α level of $P < 0.05$ was used in all analyses to evaluate the significance of treatment effects or correlations.

RESULTS AND DISCUSSION

Weather Conditions

Weather conditions were reported previously in Bourguignon et al. (2019). Briefly, most months each year were within the expected range of the 30-year long-term mean for temperature (Fig. 1). However, rainfall generally was greater than the 30-year long-term mean for much of late spring and summer in both years (Fig. 1).

Lignocellulose concentrations

Cellulose, hemicellulose, and lignin were analyzed in bast and core of samples harvested in 2014 and 2015, using a modified ANKOM procedure (Vogel et al., 1999). Our study was one of the first to estimate cellulose concentration in response to row spacing, seeding rate, N rate, and variety, for each kenaf fiber tissue. The overall results showed that the lignocellulose component concentrations in bast and core fibers differed among all practice. For example, bast cellulose concentration was modestly affected by N rate, and ranged between 535 and 550 g kg^{-1} (Fig. 2A) and variety x N rate interaction was non-significant (Table 1). In contrast, in the core, cellulose concentration was approximately 6% greater for Whitten than for Tainung 2, but the difference between cultivars was greater when no N was applied (510 g kg^{-1} for Whitten, and 460 g kg^{-1} for Tainung 2, Fig. 2A). These results related to N treatment effects differed from Adamson et al. (1979), in which N fertilization had no effect on cellulose concentration. Other studies have provided results for concentration of cellulose in core and bast, but without regard to agronomic production practices or varietal comparisons (Ashori et al., 2006; Abdul Khalil et al., 2010).

The results also indicated that, in general, Whitten contained greater cellulose concentration core fiber than did Tainung 2, which means that producers may use Whitten instead of Tainung 2 in order to produce kenaf for cellulose. The bast cellulose concentration differed due to spacing (Table 1) but cellulose concentration in core fiber was not influenced by row spacing (Table 2), documenting that management practices can influence component fiber concentrations differentially. Cellulose concentration in bast tissue was greater when kenaf was planted at 371,000 seed ha^{-1}. Greater cellulose concentration could benefit the production of some products, such as higher quality paper (Bel-Berger et al., 1999).

Few studies have detailed the lignocellulose components of kenaf bast and core in response to management practices and variety. However, determination of cellulose concentration was studied in the context of its use as source for paper and pulp, and natural fibers for biocomposites (Saba et al., 2015), who reported cellulose concentrations of 692 g kg^{-1} and 321 g kg^{-1} in bast and core, respectively, quite different than what was found in this study. Likewise, prediction of biofuel production can vary by the method used to quantify fibers, including cellulose. Although we used the protocol of Vogel et al. (1999) to determine cellulose concentration, it is unlikely that quantification method alone would explain the large differences between the two studies.

Cellulose in bast was negatively correlated with stem height and core:bast ratio (r = -0.48 and -0.31, respectively), whereas cellulose in the core was negatively correlated to stem dry yield, stem height, core:bast ratio (r = -0.29, -0.69, -0.48, respectively). This indicated that measurement of stem height and core:bast ratio at harvest could be a useful tool to predict cellulose concentration in both bast and core. The correlation between cellulose and height was previously observed by Adamson and Bagdy (1975). In their study, monoethanolamine cellulose in the whole plant, averaged over 47 kenaf breeding lines tested, was found to be positively correlated to plant height (r = 0.16). However, they did not take into account the different fiber tissues so it is not possible to determine if the relationship was specific to core, bast, or stem tissue in general.

In our study, hemicellulose concentration in bast and core was sensitive to the interaction of variety × seeding rate × row spacing (Tables 1 and 2, Fig. 2B), but without a clear pattern. Hemicellulose concentration in the bast of Tainung 2 was slightly greater when kenaf was planted at 247,000 seed ha^{-1} in 76-cm rows or at 371,000 seed ha^{-1} in 38-cm rows, compared to the other combination of treatments (Fig. 2B). A difference between treatments was observed for Whitten planted at 371,000 seed ha^{-1} in 76-cm rows, which had slightly greater core cellulose concentration than under the same seeding rate but using 38-cm rows (Fig. 2A). In the same core tissue, hemicellulose concentration was 4% greater when 224 kg N ha^{-1} was applied than when other N rates were used (Table 2). This result was different than Bourguignon et al. (2016b), in which hemicellulose concentration in both bast and core was significantly influenced by N fertilization.

Very few studies have documented differences in hemicellulose concentration due to management practice by variety interactions. Saba et al. (2015) reported hemicellulose concentration in the bast and in the core of 272 and 410 g kg^{-1}, respectively, contrasting with the results obtained in this study. Additionally, Ashori et al. (2006) reported disparate results for hemicellulose concentrations in core and bast, as did Abdul Khalil et al. (2010) (calculated as holocellulose – cellulose). On average in our study, hemicellulose in bast and core were 135 and 185 g kg^{-1}, respectively (calculated from results in Tables 1 and 2). Differences among studies for hemicellulose and other lignocellulosic concentrations could be explained by a divergence of variety and methodologies used to analyze the kenaf fibers. In this study, we evaluated interactions of genotype × management practices, rarely studied with kenaf. Despite finding differences within bast and core fibers for hemicellulose concentration due to agronomic management practices, differences were substantially less than for cellulose concentration in this study.

Lignin concentration in the bast was not impacted by any of the treatments (Table 1), but the lignin concentration in the core was influenced by seeding rate and N rate (Table 2). The core tissue of kenaf planted at 247,000 seed ha^{-1} contained 3% less lignin than when grown at 371,000 seed ha^{-1} and using 112 or 224 kg N ha^{-1} resulted in a 4% increase of lignin concentration compared to the control. The effects of N fertilization on lignin concentration were similar to those reported by Adamson et al. (1979).

Considering that the lignin determination followed the Vogel et al. (1999) protocol, the concentrations were in fact, values for ADL, as studied in Goff et al. (2012). As kenaf is closer in nature to woody materials than forage species as described in Goff et al. (2012), roughly doubling the ADL provides a good estimate of Klason lignin. Therefore, the ADL results of this study were well below the 280 and 252 g kg^{-1} for bast and core lignin reported by Saba et al. (2015). Lignocellulosic concentration is critical to evaluate a crop's potential for lignocellulosic feedstock. Kenaf was found to be competitive with other biomass feedstock such as switchgrass, corn stover, and loblolly pine due to the combination of its lignocellulose concentrations and yield (Kuzhiyil et al., 2012).

Total ash, carbon, and nitrogen concentration

Total ash concentration in biomass is important when evaluating biofuel substrate potential. The presence of ash, and particularly K, can cause slagging or fouling during conversion processes (Fahmi et al., 2007). The ash concentration in the bast and core portion of the stem was influenced by all treatments except row spacing. In the bast, the ash concentration varied between 80 and 95 g kg^{-1}, depending on seeding and N rate (Table 1, Fig. 3A). In the core, the ash concentration varied between 30 and 45 g kg^{-1}, depending on variety, seeding, and N rate (Table 2, Fig. 3B). In the core, increased fertilizer N application resulted in lower total ash concentration for both varieties with a few exceptions. For instance, when kenaf was planted at 247,000 seed ha^{-1} and received 168 kg N ha^{-1}, both Tainung 2 and Whitten had a similar total ash concentration (about 40 g kg^{-1}, Fig. 3B).

For both core and bast, fertilizer N rate influenced ash concentration, which was also reported by Anfinrud et al. (2013). However, they did not describe the interaction in detail. A similar interaction was reported for switchgrass (*Panicum virgatum* L.) where increasing N fertilization resulted in lower total ash concentration (Lemus et al., 2008). In our study, additional N fertilization resulted in lower ash concentration for both bast and core, however trends were not wholly consistent (Fig 3A; 3B). This may be a response in non-N fixing plants in general, simply due to increased N accumulation in response to greater N availability, uptake, and accumulation. Our study not only detected this interaction, but it also showed that row spacing and seeding rate significantly influenced ash concentration (Fig. 3B). The decrease in total ash concentration when N fertilization increased was a positive result, because it could mean that, even though N fertilization was not beneficial for stem yield, it could result in a cleaner feedstock for disparate industrial products, including higher quality paper and biofuel.

Regardless of row spacing, seeding, and N fertilization rate, the results showed that there was a significant variety effect on total ash concentration in the bast. Whitten contained 6% greater ash than Tainung 2 (Table 1). At harvest, ash concentration was previously found to be 76.2 g kg^{-1} in the whole plant (Anfinrud et al., 2013), which was lower than earlier in the growing season. When differentiated, bast and core of variety ‘V36’ grown in Malaysia had 54 g kg^{-1} and 19 g kg^{-1} ash, respectively (Khalil et al., 2010), whereas bast and core of Tainung 2 in 2004/2005 studies were composed of 51 g kg^{-1} and 21 g kg^{-1}, respectively (Bourguignon et al., 2016b). These various studies provided evidence of a genetic influence on kenaf total ash concentration, which was also found in our study. Not only was total ash concentration different among fiber tissues, but differences among varieties were also observed. Ash concentration can impact kenaf end-use applications and industrial production efficiencies. Indeed, total ash presence was reported to cause problems during biomass conversion, reducing the biomass heating value and ethanol production (Anderson et al., 2010; Demirbas, 2002). Greater ash in substrate also impacts biocomposite applications, as thermal stability of a composite decreases as ash concentration increases (Lee et al., 2009; Yang et al., 2005). Tainung 2 would be a better variety to grow if producers wanted to grow kenaf for biofuel or biocomposite purpose, especially using the bast portion of kenaf.

A unique aspect of this study was that bast and core samples were analyzed for C and N concentrations. Results are presented using C:N ratios, which showed sensitivity to treatments (Tables 1 and 2). The C:N ratio was 8% greater in the bast when kenaf was grown in 38-cm rows than in 76-cm rows and gradually decreased as fertilizer N was increased (Table 2). Growing kenaf in 38-cm in 2014 resulted in a 17% increase of C:N ratio in the core tissue, compared to 76-cm rows (Table 2). Similarly to the bast, the C:N ratio in the core gradually decreased with an increase of N fertilization. With respect to variety and seeding rate treatments, the C:N ratio in the bast was 11% greater for Tainung 2 seeded at 371,000 seed ha^{-1} than the other combinations of variety and seeding rate (Fig. 4). Greater C:N ratios often are preferable for industrial products from biomass, including paper and biofuel where N in feedstock is viewed largely as a contaminant. These results indicate that management practices can influence kenaf composition, with differential partitioning between bast and core and deposition of C and N.

Previously, we reported that genotype and management practices interacted to affect kenaf stem and fiber productivity, morphology, and composition (Bourguignon et al., 2019). An important result previously reported was that N fertilization did not increase stem DM yield, regardless of how much N was applied (Bourguignon et al., 2019). However, it was noted that increased N fertilization rate did contribute to greater stem height and diameter during the growing season, as well as plant density at harvest, but N fertilization did not increase overall stem fiber yield. The current report found that increasing N fertilization rate decreased cellulose concentration of bast fiber in both cultivars while concomitantly increasing core cellulose concentration in only one entry, Whitten. Additionally, ash concentration in general decreased with increasing N rate, and this may be important for fiber and biofuel processors as greater ash concentrations often can decrease chemical or biochemical processing efficiencies. However, the magnitude of these potential responses is dependent on the specific end product desired and processes used.

CONCLUSIONS

Selection of a specific kenaf variety and applying the appropriate agronomic management practices will be important for optimizing bast and core fiber components as substrate for bioeconomy products, including paper and biofuel. Increasing N fertilization rate decreased cellulose concentration of bast fiber in Tainung 2 and Whitten while concomitantly increasing core cellulose concentration in only one entry, Whitten. Additionally, bast and core ash concentration, in general, decreased with increasing N rate.

Overall, this study provides new evidence that kenaf can be successfully grown in the upper Midwest, US and could be an alternative crop for row-crop producers. Kenaf has promising potential as a multi-purpose crop that could contribute to diversification of the agricultural landscape, natural fiber market, and regional economy.

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Figure 1. Monthly cumulative precipitation and average air temperature in 2014 and 2015, Boone, Iowa.

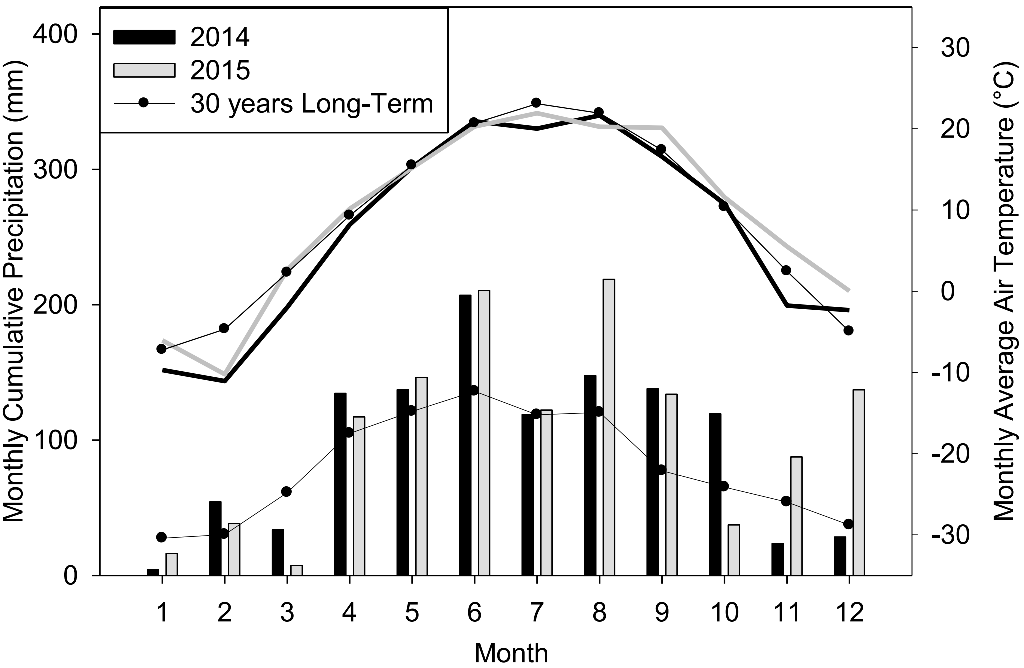

Figure 2. Cellulose concentration (mean ± S.E.), influenced by variety × N rate (A) and hemicellulose concentration (mean ± S.E.), influenced by variety × row spacing × and seed rate (B) of bast and core, when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters in panel A denote significant differences between variety × N rate treatments (Tainung, bold; Whitten, standard), whereas different letters in panel B indicate significant differences between variety × row spacing × seed density treatments. Note that the scale of the y-axis of panel A does not start at 0.

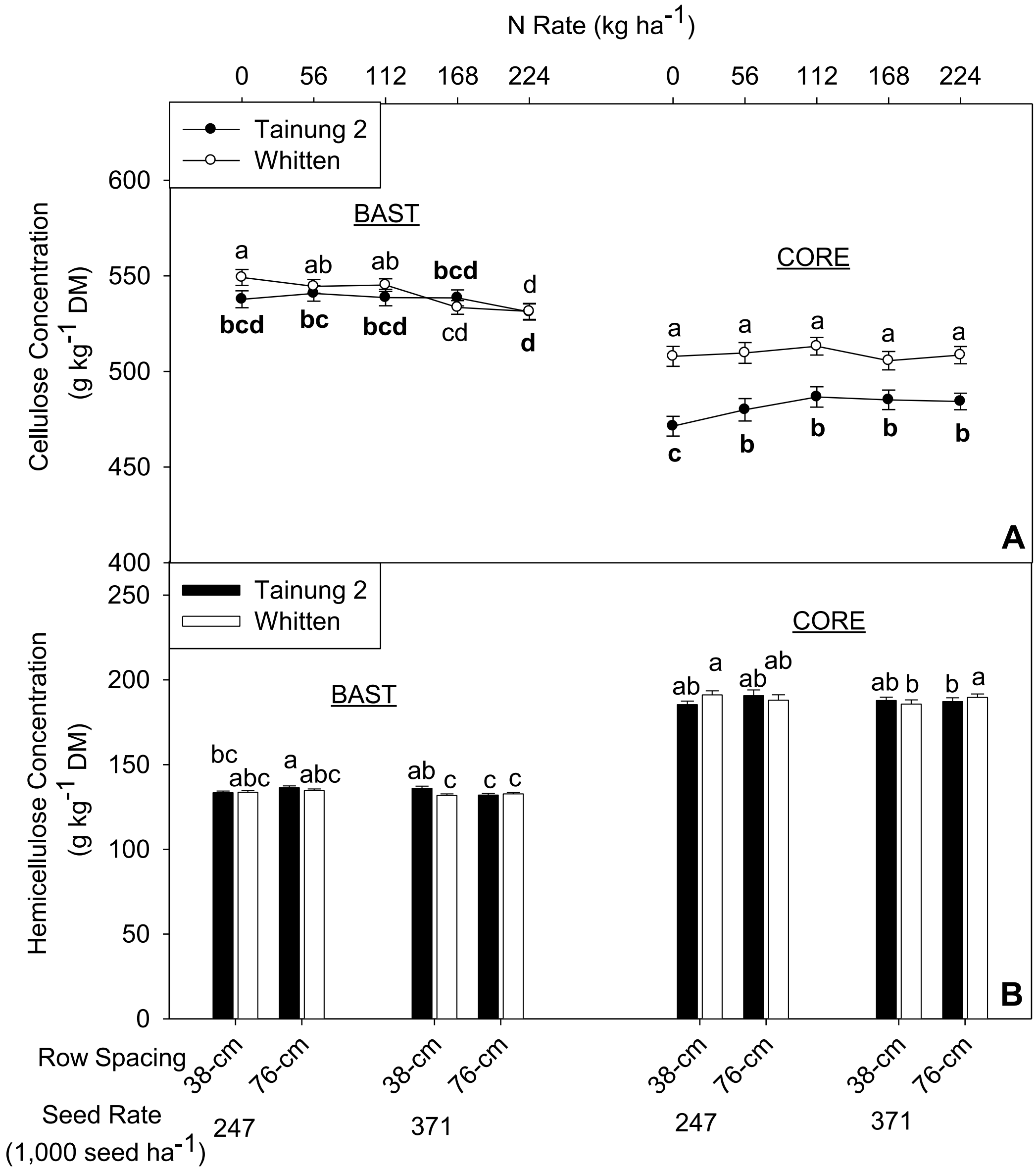

Figure 3. Total ash concentration in bast and core (mean ± S.E.), influenced by seed × N rate (A) and ash concentration (mean ± S.E.), influenced by variety × seed × N rate of the core (B), when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters in panel A denote significant differences between seed rate × N rate treatments (247,000 seed ha^{-1}, bold; 371,000 seed ha^{-1}, standard).

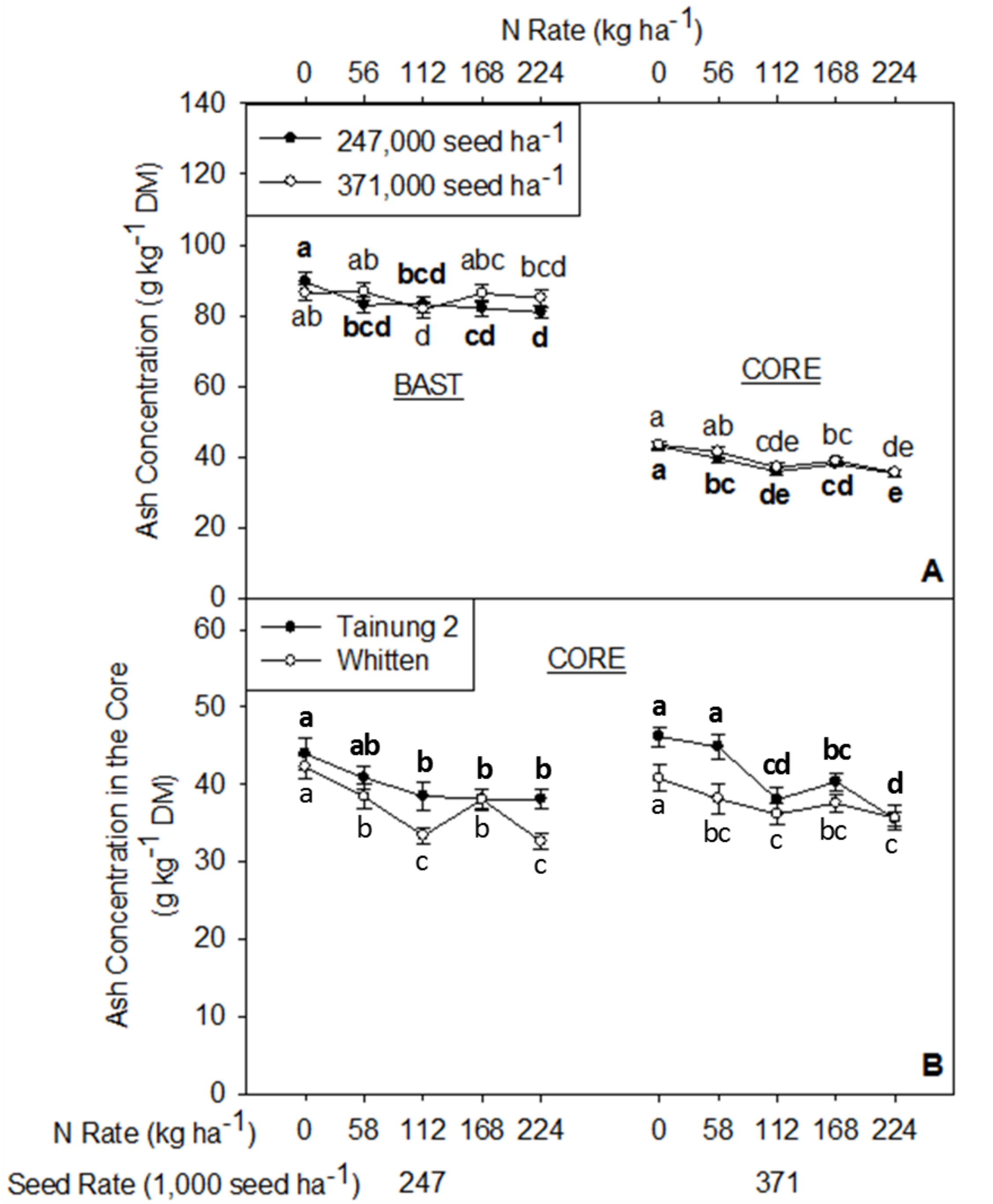

Figure 4. Carbon:nitrogen ratio (mean ± S.E.) of Tainung 2 and Whitten plants, when grown at 247,000 and 371,000 seed ha^{-1} at Boone, IA in 2014 and 2015, averaged over row

spacings and N rates. Different letters on top of the bars indicate significant differences between variety × seed density treatments, for bast and core, analyzed separately.

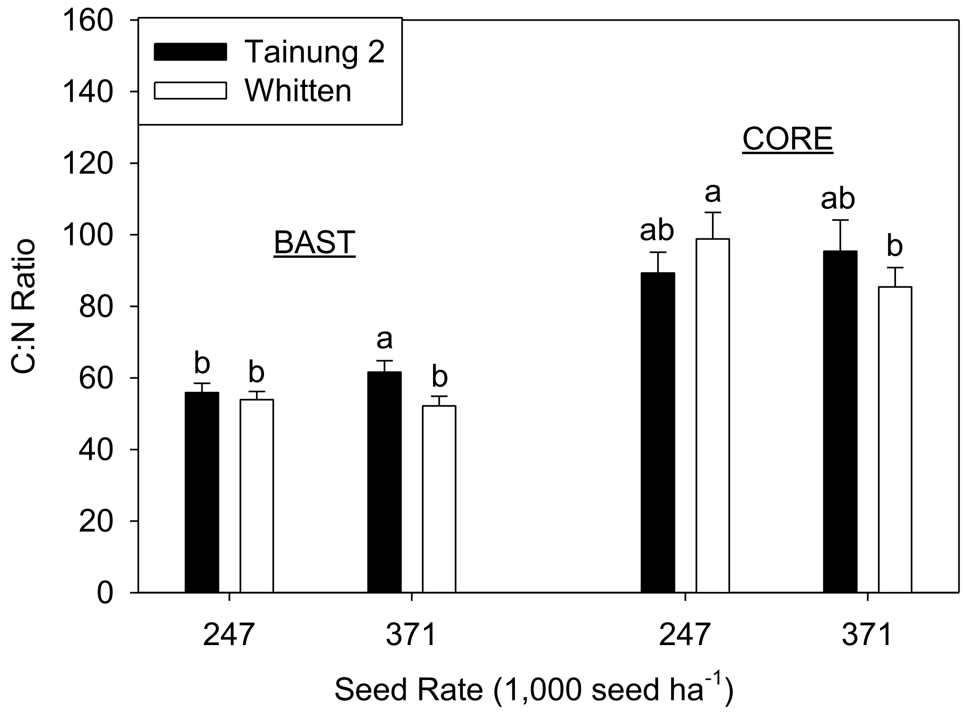

Table 1. Lignocellulose components, total ash concentration, and C:N ratio of kenaf bast as influenced by variety, row spacing, seed density, and nitrogen rate. Boone, IA, 2014 and 2015.

Treatment	df	Cellulose	Hemicellulose	Lignin	Ash	C:N Ratio†
		——— g kg^{-1} DM† ———				
Variety						
Tainung 2		537 a‡	134 a	55 a	82 b	59 a
Whitten		541 a	133 a	55 a	87 a	53 b
SED		2.7	0.7	0.9	1.3	1.7
Row Spacing						
38-cm		540 a	134 a	55 a	83 a	58 a
76-cm		538 a	134 a	55 a	86 a	54 b
SED		2.7	0.7	0.9	1.3	1.7
Seed Density						
247,000 seed ha^{-1}		536 b	135 a	56 a	84 a	54 a
371,000 seed ha^{-1}		542 a	133 b	55 a	85 a	57 a
SED		2.7	0.7	0.9	1.3	1.7
Nitrogen Rate						
0 kg N ha^{-1}		543 a	134 a	55 a	88 a	78 a
56 kg N ha^{-1}		543 a	133 a	56 a	85 b	70 b
112 kg N ha^{-1}		542 a	134 a	56 a	82 b	54 c
168 kg N ha^{-1}		536 b	133 a	55 a	84 b	42 d
224 kg N ha^{-1}		531 b	134 a	54 a	83 b	36 e
SED		2.9	1.2	1.0	1.5	2.1
				ANOVA		
Source	df					
Variety (V)	1	ns	ns	ns	***	**
Row Spacing (R)	1	ns	ns	ns	ns	**

V × R	1	ns	ns	ns	ns	ns
Seed Density (S)	1	*	*	ns	ns	ns
V × S	1	ns	ns	ns	ns	*
R × S	1	ns	*	ns	ns	ns
V × R × S	1	ns	*	ns	ns	ns
Nitrogen Rate (N)	4	***	ns	ns	**	***
V × N	4	ns	ns	ns	ns	ns
R × N	4	ns	ns	ns	ns	ns
V × R × N	4	ns	ns	ns	ns	ns
S × N	4	ns	ns	ns	*	ns
V × S × N	4	ns	ns	ns	ns	ns
R × S × N	4	ns	ns	ns	ns	ns
V × R × S × N	4	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability levels.
† C:N, Carbon:nitrogen; DM, dry matter.
‡ Different letters denote significant differences between treatments.
ns, nonsignificant ($P > 0.05$).

Table 2. Lignocellulose components, total ash concentration, and C:N ratio of kenaf core as influenced by variety, row spacing, seed density, and nitrogen rate. Boone, IA, 2014 and 2015.

Treatment		Cellulose	Hemicellulose	Lignin	Ash	C:N Ratio†
		g kg^{-1} DM†				
Variety						
Tainung 2		481 b‡	188 a	96 a	40 a	92 a
Whitten		509 a	189 a	95 a	37 b	92 a
SED		1.9	1.4	1.0	0.8	6.5
Row Spacing						
38-cm		496 a	188 a	95 a	39 a	100 a
76-cm		495 a	189 a	96 a	39 a	83 b
SED		1.9	1.4	1.0	0.8	6.5
Seed Density						
247,000 seed ha^{-1}		494 a	189 a	94 b	38 a	94 a
371,000 seed ha^{-1}		497 a	188 a	97 a	39 a	90 b
SED		1.9	1.4	1.0	0.8	6.5
Nitrogen Rate						
0 kg N ha^{-1}		490 b	188 bc	94 c	43 a	127 a
56 kg N ha^{-1}		495 ab	184 c	95 bc	41 b	127 a
112 kg N ha^{-1}		500 a	189 b	97 ab	37 d	90 b
168 kg N ha^{-1}		495 a	187 bc	94 c	39 c	59 c
224 kg N ha^{-1}		496 a	193 a	98 a	35 d	56 c
SED		2.7	2.1	1.3	0.9	6.7
			ANOVA			
Source	df					
Variety (V)	1	***	ns ‡	ns	***	ns
Row Spacing (R)	1	ns	ns	ns	ns	*

V × R	1	ns	ns	ns	ns	ns
Seed Density (S)	1	ns	ns	*	ns	ns
V × S	1	ns	ns	ns	ns	ns
R × S	1	ns	ns	ns	ns	ns
V × R × S	1	ns	*	ns	ns	ns
Nitrogen Rate (N)	4	**	***	**	***	***
V × N	4	*	ns	ns	ns	ns
R × N	4	ns	ns	ns	ns	ns
V × R × N	4	ns	ns	ns	ns	ns
S × N	4	ns	ns	ns	ns	ns
V × S × N	4	ns	ns	ns	*	ns
R × S × N	4	ns	ns	ns	ns	ns
V × R × S × N	4	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability levels.
† C:N, Carbon:nitrogen; DM, dry matter.
‡ Different letters denote significant differences between treatments.
ns, nonsignificant ($P > 0.05$).